

<b>REPORT DOCUMENTATION PAGE</b>				Form Approved OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. <b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b></small>					
<b>1. REPORT DATE (DD-MM-YYYY)</b> 18-02-2015		<b>2. REPORT TYPE</b> Master's Thesis		<b>3. DATES COVERED (From - To)</b> 21-07-2014 to 11-06-2015	
<b>4. TITLE AND SUBTITLE</b>  ALTERNATIVE OPERATIONAL ENERGY OPTIONS - A NEED FOR A HOLISTIC APPROACH TO REDUCE THE LOGISTICS TAIL AND IMPROVE STRATEGIC ADVANTAGE				<b>5a. CONTRACT NUMBER</b>	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR</b>  LCDR Joseph H. Peth, SC, USN				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>  Joint Forces Staff College Joint Advanced Warfighting School 7800 Hampton Blvd Norfolk, VA 23511-1702				<b>8. PERFORMING ORGANIZATION REPORT</b>	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION / AVAILABILITY STATEMENT</b> Approved for public release, distribution is unlimited					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b>					
<b>15. SUBJECT TERMS</b>					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b> Unclassified Unlimited	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			<b>19b. TELEPHONE NUMBER</b> <small>(include area code)</small>  757-443-6301

*Intentionally left blank*

***NATIONAL DEFENSE UNIVERSITY***

***JOINT FORCES STAFF COLLEGE***

**JOINT ADVANCED WARFIGHTING SCHOOL**



**ALTERNATIVE OPERATIONAL ENERGY OPTIONS - A NEED FOR A  
HOLISTIC APPROACH TO REDUCE THE LOGISTICS TAIL AND IMPROVE  
STRATEGIC ADVANTAGE**

**by**

**Joseph H. Peth**

***LCDR, SC, USN***

*Intentionally left blank*

**ALTERNATIVE OPERATIONAL ENERGY OPTIONS - A NEED FOR A HOLISTIC  
APPROACH TO REDUCE THE LOGISTICS TAIL AND IMPROVE STRATEGIC  
ADVANTAGE**


by

**Joseph H. Peth**

***LCDR, SC, USN***

**A paper submitted to the Faculty of the Joint Advanced Warfighting School in partial satisfaction of the requirements of a Master of Science Degree in Joint Campaign Planning and Strategy. The contents of this paper reflect my own personal views and are not necessarily endorsed by the Joint Forces Staff College or the Department of Defense.**

**This paper is entirely my own work except as documented in footnotes.**

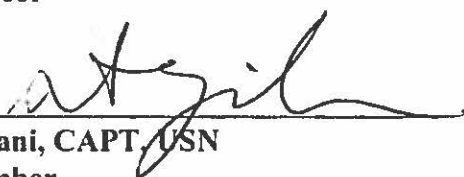
Signature: 


**18 February 2015**

**Thesis Adviser:**

Signature:   
**Dr. S. Mike Pavelec**  
**Associate Professor**

**Approved by:**

Signature:   
**Steven M. Guilian, CAPT, USN**  
**Committee Member**

Signature:   
**Dr. Robert Antis**  
**Director, Joint Advanced Warfighting School**

**Not for Commercial Use without the express written permission of the author**

*Intentionally left blank*

## **ABSTRACT**

Technological superiority is the basis for the overwhelming supremacy of the United States Military. The use of technology is critical to the success of modern military operations. The capability provided from the unrestricted use of technology gives the United States a distinct strategic advantage over its adversaries. Technology is dependent on operational energy to function; how the United States delivers operational energy to the battlefield matters. The U.S. Military needs to decrease operational energy consumption from traditional sources and leverage readily available and renewable resources of operational energy. To do this, the United States Department of Defense must aggressively pursue alternative operational energy options in order to maintain the strategic advantage of increasingly capable, highly maneuverable, and rapidly deployable forces.

## **DEDICATION**

I dedicate this thesis work to my wife Christina and my son Spencer and thank them for their patience and support throughout the year.



## **ACKNOWLEDGEMENTS**

I wish to thank my committee members CAPT S.M. Guiliani and Dr. S. Mike Pavelec who have been tremendously generous with their time and guidance. I would also like to thank Mr. Jeff Turner for his assistance in the development of this document.

*Intentionally left blank*

## TABLE OF CONTENTS

INTRODUCTION .....	1
CHAPTER 1 FUEL CELLS .....	6
CHAPTER 2 WIND POWER .....	11
CHAPTER 3 SOLAR POWER .....	17
CHAPTER 4 MICRO ENERGY HARVESTING .....	24
CHAPTER 5 OPERATIONAL IMPACTS .....	28
CONCLUSION.....	33
BIBLIOGRAPHY.....	35

## INTRODUCTION

Technological superiority has long been the basis for the overwhelming supremacy of the United States Military.<sup>1</sup> The use of technology is critical to the success of modern military operations and the capability provided from the unrestricted use of technology gives the United States a distinct strategic advantage over its adversaries. American Military technology is dependent on operational energy, specifically in the form of electricity, to make it function. To maintain its technological superiority and gain a strategic and operational advantage, the U.S. Military needs to decrease operational energy consumption from traditional sources and leverage readily available and renewable resources of operational energy.

The Department of Defense defines operational energy as the energy required for training, moving, and sustaining military forces and weapons platforms for military operations. The term includes energy used by power systems, generators, logistics assets, and weapons platforms employed by military forces during training and in the field.<sup>2</sup> Operational energy by this definition is divided into two categories. The first category of operational energy relates to operational energy for prime movers. This encompasses trucks, tanks, ships, and aircraft, all requiring operational energy for mobility. The second category relates to operational energy for ancillary equipment. This includes alternating current/direct current (AC/DC) power supplies for electric power distribution networks or local micro-grids at forward operating areas. This study focuses on

---

<sup>1</sup> Charles Morrison, 'Technological Superiority No Longer Sufficient For US Military Dominance - AEI', AEI, last modified 2014, accessed February 5, 2015, <https://www.aei.org/publication/technological-superiority-no-longer-sufficient-for-us-military-dominance/>.

<sup>2</sup> Energy.defense.gov, 'About - Dod Operational Energy', last modified 2015, accessed February 8, 2015, <http://energy.defense.gov/About.aspx>.

operational energy for ancillary equipment.

Ancillary equipment for a company-size ground element includes electronics related to global positioning system navigation, communications, target acquisition, countering improvised explosive devices, biometric identification, night vision, weapons sighting, targeting, as well as mobile computing. Forward operating bases (FOB) supporting military operations in austere locations have additional operational energy requirements depending on the level of forward support. Ancillary equipment operational energy requirements at FOBs can include environmental control, network nodes, lighting, material handling, medical equipment operation, recreation, food preparation, civil engineering support equipment, as well as other combat service support requirements.

Today, operational energy for ancillary equipment generally comes from two sources. The first source is connected to a host nation grid. This source is not likely to be available or reliable during combat operations or in austere locations. The second source is through diesel powered generators. The Department of Defense reports that generators are the single largest battlefield consumer of operational energy.<sup>3</sup> Generators convert operational energy from diesel fuel to electrical operational energy.

Providing operational energy in support of military operations is expensive and presents risks. Costs associated with operational energy are deemed “Fully Burdened Costs of Energy” and are comprised of three elements. It includes the fuel commodity price (price of the fuel), the tactical delivery assets burden (fuel for delivery, asset depreciation, and infrastructure costs), and the security/force protection assets burden

---

<sup>3</sup> U.S. House Committee on Subcommittee on Readiness, Committee on Armed Services, Increased Attention on Fuel Demand Management at DOD’s Forward-Deployed Locations Could Reduce Operational Risks and Costs, 111th Cong., 1st sess., 2009, H. Rep. GAO-09-388T, 1-10

(costs with security requirements, asset depreciation, and route clearance costs.)<sup>4</sup>

*National Defense Magazine* provided an example of battlefield operational energy costs in 2010. The example was the Defense Logistics Agency bought fuel for \$2.82 per gallon. During peacetime, that gallon of fuel cost \$13 when shipped by ground to a forward-deployed location. In hostile areas, prices can range from \$100 to \$600 for “in theater” delivery. The Army estimated fuel costs of up to \$400 a gallon if the only way to ship it was via helicopters.<sup>5</sup> In 2012, the operational energy requirements in Afghanistan alone included 13 million barrels<sup>6</sup> of fuel for vehicles, aircraft, ISR equipment, as well as diesel powered electric generators used at combat outposts and FOBs.<sup>7</sup> The costs associated with battlefield losses are staggering as well.

In June of 2008 alone 44 trucks and 220,000 gallons of fuel were lost due to attacks or other events while delivering fuel to Bagram Air Field in Afghanistan.<sup>8</sup> Resupply convoys face hazards including enemy attacks, severe weather, traffic accidents, and pilferage. Resupply casualties have historically accounted for 10%-12% of all Army casualties - the majority related to fuel and water transport.<sup>9</sup> For every one of the 866,181 soldiers officially counted as injured casualties in Iraq and Afghanistan, the

---

<sup>4</sup> Alan Bohnwagner, “An Overview of the Fully Burdened Cost of Energy (FBCE),” Assistant Secretary of Defense for Operational Energy Plans and Programs (blog), December 11, 2013, accessed December 13, 2014, <http://energy.defense.gov/Blog/tabid/2569/Article/7364/an-overview-of-the-fully-burdened-cost-of-energy-fbce.aspx>.

<sup>5</sup> Sandra Erwin, “How Much Does the Pentagon Pay for a Gallon of Gas?,” *National Defense*, April, 2010, <http://www.nationaldefensemagazine.org/archive/2010/April/Pages/HowMuchforaGallonofGas.aspx>

<sup>6</sup> One barrel equals 42 Gallons of fuel

<sup>7</sup> U.S. Department of Defense, Fiscal Year 2012. Operational Energy Annual Report, open-file report, U.S. DoD (Washington, DC: Government Printing Office, 2013), [http://energy.defense.gov/Portals/25/Documents/Reports/20131015\\_FY12\\_OE\\_Annual\\_Report.pdf](http://energy.defense.gov/Portals/25/Documents/Reports/20131015_FY12_OE_Annual_Report.pdf)

<sup>8</sup> U.S. House Committee on Subcommittee on Readiness, Committee on Armed Services, Increased Attention on Fuel Demand Management at DOD’s Forward-Deployed Locations Could Reduce Operational Risks and Costs, 111th Cong., 1st sess., 2009, H. Rep. GAO-09-388T, 1-10

<sup>9</sup> Army Environmental Policy Institute, Sustain the Mission Project: Casualty Factors for Fuel and Water Resupply Convoys, CTC-CR-2009-163, Washington D.C.:GPO 2009 [http://www.aepi.army.mil/docs/whatsnew/SMP\\_Casualty\\_Cost\\_Factors\\_Final1-09.pdf](http://www.aepi.army.mil/docs/whatsnew/SMP_Casualty_Cost_Factors_Final1-09.pdf)

government is expected to spend some \$2 million in long-term medical costs.<sup>10</sup>

Considering those figures, the long-term medical costs associated with the delivery of operational energy is approximately 175 billion dollars. Petroleum based fuels also create other strategic issues. Oil prices affect military budgets and result in money being moved from other programs. Reducing the operational energy requirements also reduces the vulnerability of the U.S. Military to oil price fluctuations and increases financial stability.

There are three choices the United States military can make concerning operational energy for ancillary equipment. First, the United States military could choose operational energy status quo. The choice maintains the current level and method of logistics support in use today and keeps the associated risks, costs, and limitations associated with current operation methods.

The second option is to reduce technological capability and dependence on operational energy accepting the risks involved with less capability. For example, a commander could choose not operating equipment dependent on operational energy such as environmental control units (ECUs). If commanders halted ECU operations to conserve fuel they would reduce the logistics tail, but would be constrained by reduced capability for personnel and equipment due to non-optimal environmental conditions.

The third option is to decrease operational energy consumption from traditional sources and leverage readily available and renewable resources of operational energy. To do this, the United States Department of Defense must aggressively pursue alternative operational energy options in order to maintain the strategic and operational advantage of

---

<sup>10</sup> David Francis, "Each Injured Us Soldier Will End up Costing \$2 Million on Average," Fiscal Times, May 15, 2013, accessed December 14, 2014, <http://www.businessinsider.com/it-will-cost-2-million-for-each-injured-us-soldier-from-iraq-and-afghanistan-2013-5>.

an increasingly capable, highly maneuverable, and rapidly deployable forces.

Finding alternative operational energy solutions provides not only tactical and operational advantages, but a strategic advantage as well. Combatant Commanders depend on the ability of forces in their area of responsibility (AOR) to operate and create the effects that accomplish objectives and required strategic end states as expressed in strategy and delineated in theater campaign plans. The 2012 Department of Defense Strategic Guidance calls for a future military force that is “agile, flexible, and ready for the full range of contingencies,” and prepared for a complex, global security environment.<sup>11</sup> Reducing the logistical tail required for the support of forces in an AOR increases their maneuverability as they are not as dependent on the support mechanism that must accompany modern forces.

There are several options of alternative operational energy to choose from, and the question is which technology or what combination of technologies should the U.S. military choose for its requirements. The characteristics of each alternative energy varies and each has its own benefits and limitations. Due to this variation, multiple technologies must be used to provide operational energy. This is analogous to varying munition types based on the desired effect on a target and, just like munition selection, no single technology will fulfill all the requirements.

Chapter 1 through 4 provides an overview of fuel cell, wind power, solar power, and micro energy harvesting as potential viable alternative operational energy technologies. Chapter 5 discusses the operational impact of pursuing these alternative operational energy options for the U.S. Military.

---

<sup>11</sup> U.S. Department of Defense, Fiscal Year 2012 Operational Energy Annual Report, open-file report, U.S. DoD (Washington, DC: Government Printing Office, 2013), [http://energy.defense.gov/Portals/25/Documents/Reports/20131015\\_FY12\\_OE\\_Annual\\_Report.pdf](http://energy.defense.gov/Portals/25/Documents/Reports/20131015_FY12_OE_Annual_Report.pdf)



## CHAPTER 1 FUEL CELLS

A fuel cell is a device that uses an oxidizing process to convert chemical energy from a fuel, usually hydrogen, into electricity. Hydrogen can be reformed from natural gas or other hydrocarbons including any number of hydrocarbon fuels including diesel, gasoline, heptane, butane, or most any other hydrocarbon.

A fuel cell produces an electrical current. Each fuel cell has one positive electrode called an anode, one negative electrode called a cathode, a catalyst, and an electrolyte. Fuel in the form of hydrogen is delivered to the anode where a catalyst splits the negatively charged electrons from the hydrogen. After that point, the ionized hydrogen atoms carry an electrical charge.<sup>1</sup> The electrons from the anode are unable to pass through the electrolyte to the positively charged cathode and instead travel around through an electric circuit. That is the electric current used to perform work.<sup>2</sup> The voltage produced is direct current voltage so an inverter must be used to convert to alternating current power where required.

Compared to regular heat power generation such as a diesel generator, fuel cells have numerous advantages. Fuel cells are more efficient resulting in less fuel usage, most fuel cells are nearly silent while most diesel generators produce noise levels requiring hearing protection during operation, a byproduct of the internal combustion engine is ozone depleting carbon monoxide while the fuel cell byproduct is water. Maintenance requirements on fuel cells are low because of the absence of moving parts.<sup>3</sup> With no

---

<sup>1</sup> Americanhistory.si.edu, 'A Basic Overview Of Fuel Cell Technology', last modified 2015, accessed January 29, 2015, <http://americanhistory.si.edu/fuelcells/basics.htm>.

<sup>2</sup> Energy.gov, 'Fuel Cells - Basics | Department Of Energy', last modified 2015, accessed January 27, 2015, <http://energy.gov/eere/fuelcells/fuel-cells-basics>.

<sup>3</sup> Fuelcelltoday.com, 'Fuel Cell Benefits - Fuel Cell Today', last modified 2015, accessed January 27, 2015,

moving parts and a low noise signature, they are inherently more difficult to detect by remote infrared scanning and therefore less susceptible to discovery and location by enemy forces.<sup>4</sup>

Fuel cells are scalable and applications vary from the size to power a single computer to a full utility size power station.<sup>5</sup> This means they can be used where the military has traditionally used batteries. A comparison of providing 2200 watts of energy by a fuel cell versus the requisite number of batteries resulted in a 61% reduction in weight and a 57% reduction in volume.<sup>6</sup> A fuel cell provides consistent power, to maintain that constant power over time, more fuel is added. Conversely, to maintain constant power for a longer period with a battery, a larger battery needs to be used or the battery must be recharged. A good comparison of the difference is the time required to fill the tank of a car that runs on gasoline to the time it takes recharge an electric car. Fuel cells also do not have a charge memory like batteries so they do not degrade in capacity over time.

The amount of heat produced by a fuel cell depends on the cell type. The exhaust temperature can range between 150 to 1800 degrees Fahrenheit depending on the technology type. While in some cases lower heat signatures would be ideal, as in micro fuel cells, there are some cases where waste heat may be collected to provide hot water or drive waste heat engines. Recovering the waste heat would increase the electric output or at least decrease the demand for electricity.

The University of Maryland and Redox Power Systems LLC are developing 25 KW

---

<http://www.fuelcelltoday.com/about-fuel-cells/benefits>.

<sup>4</sup> Elizabeth Delmont, "Fuel Cells Enlist in Armed Forces," *AltEnergy eMagazine*, Oct / Nov 2009, 1, accessed January 27, 2015, [http://www.altenergymag.com/emagazine.php?art\\_id=1411](http://www.altenergymag.com/emagazine.php?art_id=1411).

<sup>5</sup> Energy.gov, 'Fuel Cells - Basics | Department Of Energy', last modified 2015, accessed January 27, 2015, <http://energy.gov/eere/fuelcells/fuel-cells-basics>.

<sup>6</sup> Robert Rose, Fuel Cells: Civilian And Military, PDF, 1st ed., 2008, accessed January 31, 2015, <http://www.fuelcells.org/uploads/rosemilitary.pdf>.

Stationary fuel cell with a target weight of under 1000 pounds and size of one cubic-meter that produces electricity from natural gas, propane, or diesel. The research has three goals: to reduce the operating temperatures of the high-power-density fuel, enable a start-up time of ten minutes, and respond to load changes quickly. The changes would be a significant boost to fuel cell technology and drive down manufacturing and operating costs.<sup>7</sup> The fuel cells would use less fuel than conventional 25KW generators and the projected acquisition costs is 90% less than traditional fuel cells. They could readily be used to provide energy for military operations in austere locations.

The Office of Naval Research is developing a possible replacement for 10 KW tactical generators using a system powered by a solid-oxide fuel cell. The solid fuel generator is about the same size (61.7L x 31.8W x 36.2H inches) and weight (538 kg /1,185 lbs.) as the current system, while consuming 44% less fuel than the diesel powered system. The installed fuel reformer generates hydrogen gas from readily available hydrocarbon based fuels including JP-8 and diesel. It is nearly silent. The “low noise” diesel generator creates 70 decibels of noise at 23 feet. That is comparable to a vacuum cleaner in operation. The fuel cell’s only noise comes from a cooling fan that makes a noise comparable to a refrigerator in operation. The fuel cell system also benefits from a reduced heat signature when compared to the diesel-powered system.<sup>8</sup>

In May 2009, Adaptive Materials demonstrated an iRobot scout unmanned guided vehicle. The iRobot covered a distance of 40 miles at a constant speed of 3.1 mph. The

---

<sup>7</sup> Maryland Technology Enterprise Institute, Meet The Potential Future Of Electricity Generation Redox Power Systems, UMD Develop Breakthrough Fuel Cells That Bring Efficient, Green, Affordable, Always-On Electricity To Businesses And Homes, 2014, accessed February 1, 2015, [http://mtech.umd.edu/news/press\\_releases/redox\\_wachsman\\_fuel\\_cells.html](http://mtech.umd.edu/news/press_releases/redox_wachsman_fuel_cells.html).

<sup>8</sup> Thomas Overton, 'Fuel Cell Unit Could Replace Tactical Diesel Generators For U.S. Military', Power, 2013, accessed January 27, 2015, <http://www.powermag.com/fuel-cell-unit-could-replace-tactical-diesel-generators-for-u-s-military/?printmode=0>.

unmanned guided vehicle operated on a 150-watt fuel cell system with a peak output of 600 watts for a period of twelve hours. Using 24 oz. of commercially available propane gas, the fuel cell system powered the unmanned guided vehicles onboard cameras and computers. During comparative testing, a battery powered model provided only 40 minutes of operation. The fuel cell technology adaptation dramatically increased range and mission time at reduced cost.<sup>9</sup>

The Army Communications-Electronic Command, the Marine's Expeditionary Program, and scientists from the Pacific Northwest National Laboratory developed a 100-watt fuel cell system capable of recharging batteries and powering electronics. The device runs on methanol fuel processed into hydrogen and is the "size of a half-gallon of ice cream." It allows soldiers to carry only one battery and recharge it from the fuel cell.<sup>10</sup> This significantly reduces the weight carried giving soldiers increased range and speed.

Fuel cells are also being developed to increase the capabilities of UAV systems and increase and significantly improve battlefield surveillance capability. The Naval Research Laboratory modified a previously battery powered small size UAV to utilize a hydrogen-powered fuel cell with flight time results that exceed the longest previous small UAV flight achieved regardless of technology and demonstrated seven times the endurance capability of the advanced battery powered model.<sup>11</sup> Tests resulted in flight times exceeding 24 hours with a six-pound payload.

The use of the fuel cell technology allows greater time on station and decrease the

---

<sup>9</sup> Elizabeth Delmont, "Fuel Cells Enlist in Armed Forces," *AltEnergy eMagazine*, Oct / Nov 2009, 1, accessed January 27, 2015, [http://www.altenergymag.com/emagazine.php?art\\_id=1411](http://www.altenergymag.com/emagazine.php?art_id=1411).

<sup>10</sup> Elizabeth Delmont, "Fuel Cells Enlist in Armed Forces," *AltEnergy eMagazine*, Oct / Nov 2009, 1, accessed January 27, 2015, [http://www.altenergymag.com/emagazine.php?art\\_id=1411](http://www.altenergymag.com/emagazine.php?art_id=1411).

<sup>11</sup> AENews, 'Fuel Cell Powered UAV Completes 23-Hour Flight', last modified 2009, accessed January 27, 2015, <http://www.alternative-energy-news.info/fuel-cell-powered-uav-flight/>.

number of launches required to collect data providing the benefit of less effort on the part of operating crews and less wear and tear on the UAV itself.<sup>12</sup> In 2013, The Office of Naval Research again broke a record with a flight exceeding 48 hours through changing the fuel to liquid hydrogen versus gaseous hydrogen. The overall push is to combine alternative operational energy systems including solar or wind power with the technology to create an onboard electrolyzer to separate hydrogen from water to run the fuel cell. The low heat signature and virtually silent operation makes the system difficult to detect.<sup>13</sup>

There are drawbacks to fuel cells. Although they are more efficient than a diesel generator, they still require fuel in the form of hydrogen to provide electricity. Additionally, the process of separating hydrogen from hydrocarbons requires energy that lowers efficiency. Supplying pure liquid hydrogen for fuel cell operation is not a good option as the specialized handling makes the transportation costs expensive. The production of fuel cells requires catalysts laden with materials like platinum, which is currently as expensive per ounce as gold.

Fuel cells do however provide significant advantages over the current method of diesel generator provided operational energy. Their silent operation, the absence of pollution, scalability, efficiency, and weight advantage make them good candidates for providing military operational energy. Scientists and researchers continue to promote efforts to reduce the costs associated with production and increase possibilities for fuel choices. A complementary operational energy technology such as wind power might be used for the electrolysis of water into hydrogen and oxygen for use in fuel cells.

---

<sup>12</sup> Onr.navy.mil, 'Ion Tiger - Office Of Naval Research', last modified 2015, accessed February 1, 2015, <http://www.onr.navy.mil/Media-Center/Fact-Sheets/Ion-Tiger.aspx>.

<sup>13</sup> Ben Coxworth, 'Ion Tiger Sets New UAV Endurance Record', Gizmag.Com, last modified 2013, accessed February 1, 2015, <http://www.gizmag.com/ion-tiger-uav-endurance-record-nrl/27491/>.

## CHAPTER 2 WIND POWER

Wind energy is created when wind, the natural movement of air from high pressure to low pressure areas, is captured and converted into mechanical energy. That mechanical energy is converted into electrical energy through a generator. The first windmills were used to pump water or grind grain. The first documented design was of a Persian windmill with vertical sails made of bundles of reeds or wood attached to a central vertical shaft by horizontal struts. The Chinese also used vertical-axis windmills with the earliest one documented by statesman Yehlu Chhu-Tshai in 1219 A.D.

Even with the adaptation of steam and petroleum based engines, wind mills stayed in use, particularly in remote and austere locations where power requirements were low and intermittent. The increasing use of electricity in the early 1900s and the study of aerodynamics and experiments revived the wind machine. During WWI, Denmark produced many wind driven generating plants rated between 20KW and 35KW due to lack of oil. Use dwindled during the inter war period, but resurged again during WWII as oil supplies became an issue again. During WWII and into the post war years, Denmark, France, Germany, and Britain all began developing wind energy technology. Most of the efforts proved technically successful, but not financially prudent.<sup>1</sup> Wind technology tends to resurge when the cost of petroleum rises as it did during the energy crisis of the 1970's. Wind turbines are divided into two categories that include horizontal axis and vertical axis.

Horizontal-axis wind turbines have a main rotor driving an electrical generator on

---

<sup>1</sup> Dennis G. Sheppard, United States. NASA Contractor Report 4337, DOE/NASA/5226-1 Historical Development of The Windmill. Washington, D.C.: National Aeronautics and Space Administration, 1990.

a tower. The base rotates so that the blades face either into or away from the wind depending on the blade type. There are two types of blades used and they are light, durable and corrosion-resistant often made from fiberglass, reinforced plastic, or a combination of both. Drag style blades are flat, produce considerable torque and work well in light wind but are not as efficient in medium to high winds. Lifting blades with a cross section similar to an airplane wing are used on most modern wind turbines. They convert significantly more power in medium and higher winds than drag blades. Blades are attached directly to a hub just like on a propeller driven aircraft. The hub can have static mounting points, meaning the blades do not change pitch, or the hub can contain a variable pitch mechanism that changes the angle of attack of the blades to increase efficiency depending on the wind speed. The blade speed is usually slower than required by a generator so a gearbox turns the slow rotation of the blades into a quicker rotation suitable for driving an electrical generator. The gearbox output shaft then drives a generator that produces AC electricity.

The generator's size is relative to desired output and wind capacity. A nacelle usually covers the gearbox and generator from the elements. The turbine is oriented in the right direction by a simple tail vane or through a controller module that monitors wind direction and changes orientation by a geared motor. Vertical-axis wind turbines operate on the same principle as horizontal axis wind turbines except that the drive shaft is set traverse to the wind and the generating components are mounted at the base of the turbine.

In general, annual average wind speeds of 11 mph are required for grid connected applications and 7-9 mph may be adequate for non-connected electrical. The minimal

wind requirements are met in many parts of the world but an evaluation of wind power density will best define an adequate source area. Wind power density indicates how much energy is available at a particular geographic area for conversion by a wind turbine and is measured in watts per square meter.<sup>2</sup>

Wind systems, regardless of type, are a relatively clean fuel source that do not create atmospheric emissions as compared to fossil fuel driven generators. Wind supply is relatively abundant and generally sustainable regardless of geographic location.

Vertical-axis wind turbines, also known as a traverse axis wind turbines, facilitate the ground mounting of gearbox sets and generators to provide improved access to moving components for ease of maintenance. Unlike horizontal-axis wind turbines, vertical-axis wind turbines do not need to face the wind. This omni-directional capability allows them to be manufactured without vane or gear orienting mechanisms required with horizontal axis wind turbines.

Vertical axis wind turbines have several advantages over other types of turbines. They do not require orientation mechanisms because they always face the wind. Their greater surface area allows for the increased capture of energy and they are more efficient in gusty winds. They can be installed in more locations including on roofs, along highways, and in parking lots. They do not pose as great a risk to birds and wildlife as they are slow moving and highly visible. They are scalable depending on the application for an output anywhere from milliwatts to megawatts. They are inherently simpler, less expensive to build, and have a lower maintenance downtime because mechanisms are at

---

<sup>2</sup> Yalcin Aksu, "Turbines," Turbines Info (blog), July 05, 2011, accessed December 31, 2014, <http://www.turbinesinfo.com/horizontal-axis-wind-turbines-hawt/>.



or near ground level. They also produce less noise.<sup>3</sup> In addition, vertical axis wind turbines are shorter and less obtrusive.<sup>4</sup>

Military use of wind power continues to increase as it provides many benefits to operations. Mobile systems are quickly set up; they are designed so that they fit on strategic airlift and military transportation assets allowing for rapid deployment. Modern micro wind systems are small and non-obtrusive resulting in quiet energy for lower profile requirements.

Oshkosh Military Systems developed what they call the REMM™ Expeditionary Power system. It is a fully deployable 40-foot tall 100-kilowatt system combined with solar panels for field use. It fits in C-17 and C-130 aircraft and fits in a standard 20' ISO container. There are also other several small-scale wind systems including Arista systems that provide power for 12 and 24-volt systems that will allow soldiers to provide small-scale power and portability.

Wind Power Systems LLC is currently working on a “Black Swan” line of vertical axis wind turbines for military that provides ultra-efficient wind power system with an appropriate blade size to generate energy from even light winds. The units are made of aluminum for decreased weight, increased integrity, and ease of assembly and disassembly. The vertical axis wind turbines are compact and lightweight allowing for increased installation options. They are shipped in flat containers making them conducive for easy storage and rapid deployment. Assembly requires only two personnel and the systems have a rated output of 400 Watts.<sup>5</sup>

---

<sup>3</sup> Ibid.

<sup>4</sup> Roy L. Nersesian, *Energy for the 21st Century: A Comprehensive Guide to Conventional and Alternative Sources* (Armonk, N.Y.: M.E. Sharpe, ©2007), 312, accessed January 6, 2015

<sup>5</sup> Logan Pierson, DoD Power, Energy & Propulsion, 2015, accessed February 5, 2015,

The Air Force Research Laboratory Advanced Power Technology Office is working on proof of concept wind power alternative operational energy program to support combat training at Eielson Air Force Base near Fairbanks, Alaska. Remotely located unmanned shelters that contain equipment used to control and monitor the exercises need some form of operational energy to function. This energy has traditionally been provided by generators. The fuel for these generators has to be flown in by helicopter twice a year during September and March. Flying in the March weather of Alaska puts significant stress on the aircraft. To alleviate flying in a more risk prone environment, the Air Force is working to extend the time between refueling so they can deliver at a more hospitable time. They intend to do this by using wind energy augmentation. The solution reduces demand for fossil fuels at the remote arctic shelters. The power system is expected to have a one-year return on investment and improve safety by shifting refuel trips into periods of calmer weather.<sup>6</sup>

Challenges exist with wind technology. Wind strength is not always constant and can vary from zero mph to hurricane force winds resulting in highly variable energy output. Winds at low speeds may not be enough to overcome the inertia of the system and higher winds can render turbines inoperative for safety reasons and will result in zero energy production. Some of these problems may be overcome through advances in sensors and control mechanisms to make continuous direction and blade position adjustments to ensure optimum efficiency and allowing the system to operate in winds that would be otherwise a danger to the system.<sup>7</sup> When increased amounts of electricity

---

[http://www.tacticaldefensemedia.com/pdf/dod/2012\\_Q2.pdf](http://www.tacticaldefensemedia.com/pdf/dod/2012_Q2.pdf).

<sup>6</sup> Wpafb.af.mil, 'Air Force Small Wind Research Improves Resiliency, Reduces Fossil Fuels Demand', last modified 2013, accessed February 6, 2015, <http://www.wpafb.af.mil/news/story.asp?id=123363697>.

<sup>7</sup> Brad Gammons, 'Technology Gains Are Powering Wind Energy (Op-Ed)', Livescience.Com, last modified

are required, larger turbines are usually the answer. This may be a problem for a military unit trying to keep a low profile.

Wind collection technology improvements focus on turbine efficiency, manufacturing cost reductions and reliability improvements. It is an extremely clean energy and provides relatively low noise levels, especially on a smaller scale. Wind is a steady power source and requires no transportation efforts. It works both day and night as long as the wind is blowing at a sufficient rate. The military technologies that are in development recognize that there are times that the weather does not cooperate with a wind driven system. Most of the “all in one” systems have back up in the form of photovoltaic solar panel systems.

## CHAPTER 3 SOLAR POWER

Solar energy is a naturally occurring and widely available power source. The sun provides approximately 100,000 terawatts of energy to the earth representing approximately 10,000 times the energy consumption rate of the entire world.<sup>1</sup> Insolation, also called solar irradiation, is defined as the rate of delivery of this direct solar radiation per unit of horizontal surface.<sup>2</sup> This is the solar energy received on a given surface at a given time. The average solar energy available on the earth is about 1000 watts per square meter.<sup>3</sup>

A viable solar power system requires several components in order to convert the energy from the sun into a useable power source. The type and quantity of components required vary depending on the method of solar energy collected. Energy obtained using semi-conductors converting sunlight into electricity is known as photovoltaic solar energy. Another technology, concentrated solar power uses mirrors to concentrate solar energy onto a small area to heat a fluid that in turn drives a turbine. Concentrated solar power systems require a large fixed geographic area making them unsuitable for expeditionary ancillary operational energy requirements for the military. The existing solution is therefore photovoltaic solar power systems.

Photovoltaic solar energy is the generation of a voltage when radiant energy falls on the boundary between dissimilar substances. In 1877, American scientist Charles Fritts improved upon the initial French theories and created a solar cell that was about 1%

---

<sup>1</sup> Michael Grätzel Philosophical Transactions: Mathematical, Physical and Engineering Sciences, Vol. 365, No. 1853, Energy for the Future (Apr. 15, 2007), pp. 993-1005 <http://www.jstor.org/stable/25190484>

<sup>2</sup> "Insolation." *Merriam-Webster.com*. Merriam-Webster, n.d. Web. 25 Jan. 2015. <<http://www.merriam-webster.com/dictionary/insolation>>.

<sup>3</sup> "Solar Power (Technology and Economics)," Electropedia, accessed January 25, 2015, [http://www.mpoweruk.com/solar\\_power.htm](http://www.mpoweruk.com/solar_power.htm).

efficient. By 1905, Albert Einstein published the theoretical framework explaining the phenomena and promoting further research in the area. Russell Ohl at Bell Laboratories successfully created a solar cell made from silicon during the early 1940s, substantially increasing the conversion efficiency to the point where energy from solar cells was able to power electronic devices.<sup>4</sup>

When light energy strikes the solar cell, electrons are knocked loose from the atoms in the semiconductor material. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons can be captured in the form of an electric current -- that is, electricity. This electricity is used to power a load, such as a light or a tool.<sup>5</sup>

Brian Towler in *The Future of Energy* describes the types of PV cells currently available. Monocrystalline silicon PV cells are the most commonly used and currently have an approximate 20% efficiency rate, mainly because they are most sensitive to infrared radiation which contains less energy than that found in the violet and ultraviolet ranges. Polycrystalline cells are cheaper to manufacture but their efficiency is less than 15% due to internal resistance near the silicon crystal boundaries. Amorphous silicon solar cells can be applied as a thin film to various substrates. Their efficiency is also currently 12.5%.<sup>6</sup> The efficiency of photovoltaic materials continues to improve with some of the experimental technologies having efficiencies as high as 44.7%.<sup>7</sup> Average efficiencies have increased from 16 to about 21% in the past three years. With a system

---

<sup>4</sup> Brian F. Towler, *The Future of Energy* (London: Academic Press, 2014), 161-68, accessed December 7, 2014, <http://proquest.tech.safaribooksonline.de/9780128010273>.

<sup>5</sup> Gil Knier "How Do Photovoltaics Work?" - NASA Science. January 1, 2002. Accessed December 7, 2014. <http://science.nasa.gov/science-news/science-at-nasa/2002/solarcells/>.

<sup>6</sup> Towler, *The Future of Energy*, 161-68.

<sup>7</sup> "Http: //www.nrel.gov/ncpv/images/efficiency\_chart.jpg," National Center for Photovoltaics, accessed December 23, 2014, <http://www.nrel.gov/ncpv/>

of 18% efficiency, solar panels could theoretically harvest 180 watts per square meter based on the concept of solar irradiation.

An example of energy availability is a solar array consisting of 36 - 240 watt frameless photovoltaic panels creating a total DC system size of 8.64kW. The system has a panel area of 525ft<sup>2</sup>, a panel roughly 24X24 feet. The cells have approximately an 18% cell efficiency. Photovoltaic solar power systems produce direct current (DC) electricity which is not conducive for running motors so it requires a power inverter to convert the electricity into alternating current (AC) electricity. Modern inverters currently consume between 4 and 8 % of the converted energy in the conversion process, which corresponds to an overall efficiency of 92 to 96 %. Therefore, the AC energy output of this system would be around 8KW. The U.S. Army field manual calls for a planning factor of .7KW per person for planning a FOB. Therefore, this system could sustain 11 persons.<sup>8</sup>

Increasing collection and conversion efficiencies and decreasing the production costs are the most promising developments in PV systems. A solar collector being developed by V3 Solar known as “The Spin Cell™” takes advantage of an outer conical shaped lens that concentrates bands of sunlight on an inner cone covered with PV cells at a consistent focal width and focal range. The lens concentrator increases electricity output and eliminates the need for tracking the sun throughout the day. Additionally, the conical array floats and rotates on installed magnets and removes heat from the system. The rotating cells reduce the heat from the solar collector while still allowing the cells to capture the light energy. This decreases production costs by allowing the system to be manufactured with less expensive and less heat-tolerant material. V3 Solar claims to be capable of generating over 20 times more electricity than a flat panel with conventional

---

<sup>8</sup> U.S. Army Field Manual 3-34.400 (FM 5-104) General Engineering, December 2008; p. E-6

PV panels.

The U.S. Military is currently using some solar applications ranging from small tactical solar panels that provide low wattage electric power for battery recharging up to a 16.4-megawatt system at Davis-Monthan Air Force Base providing power for the entire base. Several companies offer solar systems for military use. One of those systems is the Marine Austere Patrolling System (MAPS). Soldiers often carry more than 100 pounds of gear when they go on patrol. The use of solar operational energy reduces that weight. The Marine Austere Patrolling System (MAPS) combines solar power and an individual water purifier to lighten the load of Marines conducting extended missions in remote locations with limited resupply options. The MAPS system reduces the number of batteries required and water carried from 60 pounds to 13 pounds.<sup>9</sup> This can increase the operational reach and time on station for personnel on patrol.

The Marine Corps is using a solar power system by UEC, LLC called the Ground Renewable Expeditionary Energy Network System, also known as GREENS. GREENS is a lightweight and man portable solar power collection system combined with a high energy density battery system to provide electricity for electronic equipment. Each system can produce up to 1 KW of electricity and multiple systems can be run in parallel to provide up to 5 KW of electricity. The system requires no formal training for operation, deploys in less than 20 minutes, and can be used in conjunction with other energy sources. Additionally, it is approved as UN/DOT Class 9 and certified for

---

<sup>9</sup> Eric Beidel, More Power To You: Marines Boost Energy, Lighten Load, 2013, accessed January 27, 2015, Office of Naval Research, <http://www.onr.navy.mil/en/Media-Center/Press-Releases/2013/MAPS-Marine-Solar-Power-System.aspx>.

commercial shipment<sup>10</sup> The GREENS system can be used in remote locations to provide operational energy where it may not otherwise be available.

One area that does not readily come to mind when discussing the advantages of solar power is underwater. The U.S. Naval Research Laboratory, Electronics Science and Technology Division is performing research that will allow underwater systems to produce enough power to drive electronic sensors at a depth of 9meters/29.5feet. The capability allows autonomous underwater systems to operate for significantly long periods. This allows autonomous vehicles to gather data faster providing better data and clearer picture of the underwater environment. Providing power to underwater systems has been a challenge and required batteries or tethering to solar on an above water platform. Solar radiation beneath the water is lower than at the surface, however the narrow range of light waves allows for a high conversion efficiency if the solar cell is well matched to the range of the wavelength. So far, at a depth of 9.1 meters the output is 7 watts per square meter of solar cells.<sup>11</sup>

Restrictions on photovoltaic solar energy systems includes their dependence on the sun, and their varying system output depending on latitude, weather conditions, and time of day. They often require backup systems to ensure consistent power supply including large-scale battery storage and traditional operational energy systems. Central solar generating systems require large areas for deployment and some cells can be fragile depending on the type.

---

<sup>10</sup> Onr.navy.mil, 'Media Release: Solar Energy Powers Marines On Battlefield - Office Of Naval Research', last modified 2009, accessed February 6, 2015, [http://www.onr.navy.mil/en/~link.aspx?\\_id=685466B603734B9DB20FCFA8F3883E23&\\_z=z](http://www.onr.navy.mil/en/~link.aspx?_id=685466B603734B9DB20FCFA8F3883E23&_z=z).

<sup>11</sup> Nrl.navy.mil, 'Photovoltaic Cells Tap Underwater Solar Energy - U.S. Naval Research Laboratory', last modified 2012, accessed February 6, 2015, <http://www.nrl.navy.mil/media/news-releases/2012/photovoltaic-cells-tap-underwater-solar-energy>.



The photovoltaic cell energy production and collection process has distinct advantages compared to the traditional diesel powered generation method of operational energy production. Photovoltaic collection is silent and creates no air pollution. It requires no recurring fuel supply for regular energy production, thus reducing the logistics tail required for military operations. The regular operation of a solar cell energy plant has virtually no hazardous material concerns and does not require special storage, handling, or containment. Photovoltaic systems can be integrated within a local grid or micro-grid to reduce the requirements for fuel driven generators.

Smaller independent photovoltaic systems can power handheld or individual devices. Combined with a battery those systems can provide near continuous power. Additionally, most solar systems today are manufactured to be modular and easy to assemble. Some types of solar cells, such as amorphous silicon solar cells, can be applied as a thin film to various substrates. Because the cell material is thin, it can be applied to tarpaulin or tent material making a readily deployable solar photovoltaic collection system.

Making solar cells inherently more efficient is a priority for solar researchers. The most advanced cells are able to reach efficiency levels of just over 40% but remain relatively expensive. The balancing act of cost versus efficiency is a main priority. New materials including perovskites are less expensive to manufacture, more efficient at converting energy, can absorb specific wavelengths of light that current silicon based PV cells cannot capture so that layering semi-transparent sheets would increase the amount of energy collected.<sup>12</sup> The efficiencies of perovskites have increased quickly and

---

<sup>12</sup> David Glenn, "The Future of Solar: Solar Power to Surge in 2014?," CleanTechnica.com, April 05, 2014,

scientists have been able to increase perovskite efficiencies from 10% in 2012 to just over 20% by 2014. The increase to 20% may not be the most efficient technology but the quick increases in efficiency can be combined with the advantage of being produced with relatively inexpensive materials as compared to other PV technologies. Another advantage is the manufacturing process itself which costs less compared to other PV technology manufacturing technologies. Perovskite based PV cells can actually be printed directly on to glass to produce thin-film solar cells.<sup>13</sup>

Solar continues to gain ground in the market due to the increasing efficiency rates and steadily decreasing cost of photovoltaic cells. Still, it is not a technology that individually will be able to resolve the military requirement.

---

accessed January 25, 2015, <http://cleantechnica.com/2014/04/05/future-solar-solar-power-surge-2014/>.

<sup>13</sup> Uclia Wang, "Perovskite Offers Shot at Cheaper Solar Energy," *Wall Street Journal*, Sept. 28, 2014, accessed January 25, 2015, <http://www.wsj.com/articles/perovskite-offers-shot-at-cheaper-solar-energy-1411937799>.

## CHAPTER 4 MICRO ENERGY HARVESTING

Energy harvesting systems, also known as energy scavenging systems capture small amounts of wasted energy that would otherwise be lost as heat, light, sound, vibration or movement. The captured energy can be used to improve efficiencies or even replace batteries for small, low power electronic devices. Technically, solar and wind fall into this category but the energy discussed here is on a different scale. The technology is significant even though the energy levels are usually in the microwatt range. The use of the technology will continue to grow. The concept of pervasive computing, where microprocessors are embedded in everyday objects, will increase the use of energy harvesting to power these devices.

Waste energy can be captured using different materials. The most promising micro-scale energy harvesting technologies include the transfer of vibration, movement and sound transformed into electrical power using piezoelectric materials and the use of heat to harness electrical energy using thermoelectric and pyroelectric materials

When energy is converted from one form to another, there is some form of inefficiency or energy loss. An example is the heat loss from a generator. Nearly all of the world's electrical power is generated by gas engines or steam turbines that convert heat to mechanical energy, which is then converted to electricity. Approximately two-thirds of the energy input is not converted to electrical power but lost as heat. Electronics are a good example of devices that lose energy through heat and/or vibration. Think about how warm a computer or cell phone gets when in use.<sup>1</sup>

Vibration, movement and sound can be captured and transformed into electrical

---

<sup>1</sup> "Energy Harvesting," Institute of Physics, accessed January 7, 2015, <http://www.iop.org/resources/energy/index.html>.

power using piezoelectric materials. Piezoelectricity is electrical energy produced from mechanical pressure. When pressure is applied to an object, a negative charge is produced on the expanded side and a positive charge on the compressed side. Once the pressure is relieved, electrical current flows across the material.<sup>2</sup> An example of a common piezoelectric device is the microphone. It works because sound waves move a piezoelectric crystal back and forth creating electric signals.

Thermoelectric generators use waste heat to produce useable energy. They work because of a phenomenon known as the Seebeck effect where voltage is created when temperature differentials exist at the junction of two dissimilar metals. An array of these thermocouples connected together in series to a common heat source makes up a thermoelectric generator. The output depends on the temperature differential and size.

Kinetic energy solutions are being researched by The U.S. Army Armament Research, Development and Engineering Center. They are currently evaluating a knee brace with a gearbox that converts motion into electricity. This allows a soldier to recharge batteries by simply walking. It is estimated that the brace can currently generate the equivalent amount of energy as to that used during a 30-minute cellphone call.<sup>3</sup> This is similar to another device under consideration called the SPaRK -- Soldier Power Regeneration Kit being researched by SpringActive Inc. with funding from the Natick Soldier Research, Development, and Engineering Center.<sup>4</sup> Both of these options provide

---

<sup>2</sup> Maria Trimarchi, "Harvesting Energy from Human Movement," How Stuff Works, accessed January 7, 2015, <http://science.howstuffworks.com/environmental/green-science/house-music-energy-crisis1.htm>.

<sup>3</sup> Emma Roller, 'Hike, Kick, And Dance To Charge Your Gadgets', *Slate Magazine*, last modified 2015, accessed January 27, 2015,

<sup>4</sup> Pat Toensmeier, 'Design News - Guest Blogs - US Army's Boot-Based Energy Harvester Lightens Soldier's Load', Designnews.Com, last modified 2011, accessed February 6, 2015, [http://www.designnews.com/author.asp?dfpPPParams=ht%5F13%2Cindustry%5Falt%2Cindustry%5Fgov%2Caid%5F235935&dfpLayout=blog&doc\\_id=235935&page\\_number=2](http://www.designnews.com/author.asp?dfpPPParams=ht%5F13%2Cindustry%5Falt%2Cindustry%5Fgov%2Caid%5F235935&dfpLayout=blog&doc_id=235935&page_number=2).

an alternative to harvest energy to extend the range of soldiers, reduce the weight of batteries carried, and provide a consistent power source for the soldier on the move.

The Army research lab's millimeter-scale robotics is studying the feasibility of producing UAV's as small as fruit flies. Piezoelectric materials are being looked at both for the propulsion of the UAV and the power for the UAV. The small scale UAVs would serve as sensors for larger platforms and provide both situational and tactical awareness. The research involves using piezo-electric actuation to propel small-scale sensor carrying robots, both on the ground and airborne, to relay data back to a battlefield information network or other more complex sensor platform. With the right sensors, these robots may be able to detect the presence of biological or chemical compounds allowing future soldiers to pinpoint specific dangers.<sup>5</sup>

The U.S. Army Tank Automotive Research, Development and Engineering Center and GMZ Energy Corporation developed a high temperature thermo-electric generator that uses waste heat from a Bradley fighting vehicle engine. The thermoelectric generator's purpose is to reduce the load on the alternator and subsequently decrease fuel consumption of the vehicle. The unit generated over 200 watts of electricity. The generator is a subset of a larger 1000-watt system that will include five of the 200-watt thermoelectric generators. The system has another advantage in that because it converts heat to electric energy, the thermal signature of the vehicle is reduced as well.<sup>6</sup>

As the name implies, micro-energy devices do not individually provide significant

---

<sup>5</sup> Robert Ackerman, 'Army Plans Swat Teams Of Mechanical Bugs', *SIGNAL Magazine*, last modified 2010, accessed February 6, 2015, <http://www.afcea.org/content/?q=army-plans-swat-teams-mechanical-bugs>.

<sup>6</sup> BUSINESS WIRE, 'GMZ Energy Announces Successful Testing Of A 200 Watt High Temperature Thermoelectric Generator | Business Wire', Businesswire.Com, last modified 2014, accessed February 7, 2015, <http://www.businesswire.com/news/home/20140610005313/en/GMZ-Energy-Announces-Successful-Testing-200-Watt#.VNZyHzlcS73>.

amounts of energy often being measured in milliwatts. Nevertheless, they are usually small in size and the applications they are being used for do not require significant power. Energy harvesting has several advantages. First, energy harvesting is capturing energy that would otherwise be lost through waste heat or motion. The technology has the potential to reduce or remove the need for batteries and charging stations and provide continuous low power operational energy needs. Piezoelectric energy producing elements are very durable and thermoelectric elements, which have no moving parts, are extremely reliable. This permits them to provide many years of continuous operation with minimum maintenance requirements.

Research in micro energy harvesting has been in technology application, reduction of manufacturing costs, and increased power output. The development of practical uses continues to be at the forefront. The military applications of micro-energy harvesting is limitless, especially when combined with pervasive computing. Intelligence collecting sensors could operate for years collecting and relaying information. Micro energy harvesting could be used to power implantable wireless sensors that monitor the health condition or even location of soldiers on the battlefield. This technology continues to increase the effectiveness of the U.S. military.

## **CHAPTER 5 OPERATIONAL IMPACTS**

The pursuit of alternative operational energy options provides the U.S. Military with the strategic advantage of increasingly capable, highly maneuverable, and rapidly deployable forces. The continued development and implementation of alternative operational energy technologies provides significant technical advantages resulting in increased capabilities for the U.S. Military. From allowing increased access to operational environments to decreasing the impact of U.S. presence on civilian populations technology increases capability.

Military operations often call for a low profile to avoid detection. This prevents equipment from being successfully targeted, allows for maneuver to gain a positional advantage, and can assist in achieving the element of surprise. Many alternative operational energy options provide continuous power for operations without the noise and heat signature of traditional power generation resulting in a decreased probability of detection. Even in cases where traditional petroleum engines are used, alternative energy solutions like thermal electric generators can lower the heat signatures of equipment through waste heat conversion.

In cases where the military presence is more overt, such as has been the case in Afghanistan and Iraq, alternative energy solutions can minimize the impact on the environment and the civilian population. Reducing the impact on the civilian population during military operations reduces potential friction areas. This can result in a more positive or at least a less negative image of forces in an environment that can breed resentment and hinder local cooperation.

Alternative operational energy decreases fuel resupply requirements resulting in a

reduced number of required flights and convoys. This reduces the risk from enemy ambushes or encountering offensive weapons like improvised explosive devices or mines. It reduces the damage on roadways due to traffic from heavy convoy vehicles as well as relieves pressure on critical supply infrastructure capacity in the nation of operations. This allows capacity to support the needs of the indigenous population resulting in less intrusion on the local population.

Decreased supply requirements also reduces the transportation infrastructure strain on partner nations when U.S. military supply routes cross their borders. Tensions or political disagreements can result in even usually cooperative nations to limit or secure critical supply routes. From November 2011 to June of 2012, Pakistan closed supply routes through Pakistan into Afghanistan forcing the U.S. military to depend on costlier alternative routes and air bridges to support operations. The use of alternative operational energy sources would have reduced the impact on U.S. forces.

A decreased supply requirement results in a decreased need for the number of vehicles, aircraft, and ships that transport the operational energy sources. That equates to less procurement costs, fewer support personnel, and lower repair costs. It also allows the option of spending acquisition monies to purchase more direct action capability. Lower supply requirements also translates into fewer boots on the ground in harm's way. At a minimum, it means that the reduced frequency of convoys or resupply flights can allow the forces that would otherwise support those missions to provide support elsewhere and increase the ongoing operational efforts.

Alternative operational energy can also increase the operational reach of forces and equipment. The introduction of alternative operational energy shows significant gains



in time on station for unmanned aerial vehicles, autonomous surveillance systems, and robot scout vehicles. Implementation of alternative operational energy sources used in conjunction with a prime mover can also reduce the operational energy requirements of the prime mover. This is seen in the case of the 200-watt thermal electric generator that reduces the load on the vehicle's alternator. That allows the vehicle to travel further on less fuel therefore increasing its operational capability and extending its operational reach.

Alternative energy solutions that eliminate or reduce battery requirements can extend the range and time on station of troops. This allows troops on patrol to operate further away from logistics sustainment points. The sheer number of batteries used by the U.S. military is astonishing and the case is strong for implementation of alternative operational energy options to supplement battery use. The modern infantry company carries so much electronic gear over a 72-hour operating period they require more than 6,600 batteries, weighing over 1,400 pounds. The weight hinders maneuver, binds them to constant resupply, and can contribute to injuries caused by heavy packs.<sup>1</sup>

The increased use of alternative operational energy technologies provides opportunities to increase the maneuverability of modern forces. The ability for forces to move quickly, maintain on station, and require reduced logistics sustainment gives militaries the ability to maneuver more freely and can provide access to areas otherwise limited. Several factors associated with alternative operational energy can increase maneuverability in modern forces

Weight reduction is a significant factor in increasing the maneuverability of

---

<sup>1</sup> Keith Johnson, 'Fighting Form: Military Takes On Battery Fatigue', WSJ, last modified 2012, accessed February 1, 2015, <http://www.wsj.com/articles/SB10001424052702304371504577405982280891076>.

forces. The Army's Program Executive Office personnel readily admits, "Lightening the load enhances lethality, survivability and maneuverability, making soldiers more effective in any environment."<sup>2</sup> Whether it is an individual, a platoon size element, or an entire forward operating base, the reduction of weight allows soldiers to move further, stay on station longer, and reduce fatigue. It also gives soldiers greater flexibility allowing them alternatively to carry more munitions, food, or other needed items to increase their capabilities.

The ability to utilize alternative operational energy resources can allow forces to access areas where they otherwise could not operate. Take for example a humanitarian assistance or disaster relief operation where available traditional energy resources are not available or the flow has been otherwise disrupted. The concept of available technology was proven during the 2014 Rim of the Pacific exercises, alternative operational energy sources were used to power the logistics support area of the exercise using systems to produce 329-kilowatt hours of energy per day.<sup>3</sup>

Alternative energy systems also increase the deployability of military forces as well. Alternative energy systems that do not require fossil fuels are easier to maintain and can be packaged until ready for use unlike diesel generators that require regular maintenance. Most alternative operational energy systems have few moving parts and can be stored for relatively long periods without maintenance. Conversely, a diesel generator crankshaft must be turned on a periodic basis to prevent warping. This allows for ready to go, fly away methods of storage for many alternative operational energy systems.

---

<sup>2</sup> Defensesystems.com, 'Military Seeks Ways To Reduce Size, Weight And Power Of Communications Gear -- Defense Systems', last modified 2011, accessed February 1, 2015, <http://defensesystems.com/articles/2011/09/06/cover-story-communications-gear.aspx>.

<sup>3</sup> Brandon Bosworth, 'Green Energy Powers Humanitarian Training', *Ho`Okele*, 2014, accessed February 1, 2015, <http://www.hookelenews.com/green-energy-powers-humanitarian-training/>.

Because alternative operational energy systems do not require traditional fuel, the problems associated with bad fuel stocks or fuel degrading over time are also decreased.

A differing opinion on the use of alternative operational energy would be that the costs of such efforts would greatly exceed the benefits that they would provide. While expeditionary alternative energy systems do generally cost more upfront than their conventional counterparts, their decreased maintenance and support requirements drive those costs down. The In FY 2012 the Department of Defense directly spent 16.9 billion dollars on fuel costs<sup>4</sup> meaning for every 10 percent reduction, the reduction is 1.69 billion dollars. That number is in fuel savings alone, it does not count the lost lives or lost equipment. Over the life of the equipment, the total costs should be lower on the alternative operational energy equipment.

---

<sup>4</sup> U.S. Department of Defense, Fiscal Year 2012. Operational Energy Annual Report, open-file report, U.S. DoD (Washington, DC: Government Printing Office, 2013).

## CONCLUSION

The United States Military depends on operational energy to maintain a strategic, operational, and tactical advantage over its adversaries. The continued and greatly expanded use and development of alternative operational energy technologies will provide not only required support for weapons systems, but also will increase the capability, maneuverability and deployability of the U.S. Military. The plan for reducing the military's dependence on operational energy must include equipment that is more efficient as well as improved sustainable and renewable energies.

No single alternative energy technology will meet every requirement as each has strengths and weaknesses that makes it more suited for one particular environment over another. It is for this reason a diverse alternative energy portfolio must be maintained. Failure to pursue alternative energy sources can lead to increased strategic and operational risks that can be easily avoided through a holistic approach towards alternative operational energy.

Energy systems costs are compared by examining the levelized cost of energy. Lazard Corporation estimates the following costs at dollars per Megawatt hour for different sources of energy. The costs for diesel-powered generation of electricity is \$297-\$332, fuel cell power generation \$115-\$176, wind generated energy \$37-\$81, and solar PV (rooftop installation) \$180-\$265.<sup>1</sup> While the comparison is done for significantly larger output systems, the costs should be scalable to the amount of electricity being produced.

---

<sup>1</sup> Lazard Corporation, *Lazard's Levelized Cost Of Energy Analysis – Version 8.0* (Lazard, 2014), accessed February 22, 2015, <http://www.lazard.com/PDF/Levelized%20Cost%20of%20Energy%20-%20Version%208.0.pdf>.

The U.S. Military and the Department of Defense will have to focus on research and development of alternative energy sources in order to improve the mobility, efficiency, and effectiveness of forces in future warfare and maintain its technical superiority. The military's requirements for alternative operational energy are inherently unique not only because of the imperative to reduce operational costs, but due to the risks often involved in the delivery of operational energy requirements. The best way to meet the requirements is to take a holistic approach to alternative energy so that regardless of operating environment, the military can take full advantage of the benefits provided from alternative energy.

## BIBLIOGRAPHY

- AENews, 'Fuel Cell Powered UAV Completes 23-Hour Flight', last modified 2009, accessed January 27, 2015, <http://www.alternative-energy-news.info/fuel-cell-powered-uav-flight/>.
- Aksu, Yalcin "Turbines," Turbines Info (blog), July 05, 2011, accessed December 31, 2014, <http://www.turbinesinfo.com/vertical-axis-wind-turbines/>.
- Americanhistory.si.edu, 'A Basic Overview Of Fuel Cell Technology', last modified 2015, accessed January 29, 2015, <http://americanhistory.si.edu/fuelcells/basics.htm>.
- Army Environmental Policy Institute, Sustain the Mission Project: Casualty Factors for Fuel and Water Resupply Convoys, CTC-CR-2009-163, Washington D.C.:GPO 2009 [http://www.aepi.army.mil/docs/whatsnew/SMP\\_Casualty\\_Cost\\_Factors\\_Final1-09.pdf](http://www.aepi.army.mil/docs/whatsnew/SMP_Casualty_Cost_Factors_Final1-09.pdf)
- Beidel, Eric 'More Power To You: Marines Boost Energy, Lighten Load', 2013, accessed January 27, 2015, Office of Naval Research, <http://www.onr.navy.mil/en/Media-Center/Press-Releases/2013/MAPS-Marine-Solar-Power-System.aspx>.
- Bohnwagner, Alan "An Overview of the Fully Burdened Cost of Energy (FBCE)," Assistant Secretary of Defense for Operational Energy Plans and Programs (blog), December 11, 2013, accessed December 13, 2014, <http://energy.defense.gov/Blog/tabid/2569/Article/7364/an-overview-of-the-fully-burdened-cost-of-energy-fbce.aspx>.
- Bosworth, Brandon 'Green Energy Powers Humanitarian Training', Ho`Okele, 2014, accessed February 1, 2015, <http://www.hookelenews.com/green-energy-powers-humanitarian-training/>.
- Coxworth, Ben 'Ion Tiger Sets New UAV Endurance Record', Gizmag.Com, last modified 2013, accessed February 1, 2015, <http://www.gizmag.com/ion-tiger-uav-endurance-record-nrl/27491/>.
- Defensesystems.com, 'Military Seeks Ways To Reduce Size, Weight And Power Of Communications Gear -- Defense Systems', last modified 2011, accessed February 1, 2015, <http://defensesystems.com/articles/2011/09/06/cover-story-communications-gear.aspx>.
- Delmont, Elizabeth "Fuel Cells Enlist in Armed Forces," AltEnergy eMagazine, Oct / Nov 2009, 1, accessed January 27, 2015,

- [http://www.altenergymag.com/emagazine.php?art\\_id=1411](http://www.altenergymag.com/emagazine.php?art_id=1411).
- Dynamic Spin™ Technology Design Concepts,” V3Solar.com, accessed January 25, 2015, <http://v3solar.com/design-concepts/>.
- Energy Harvesting,” Institute of Physics, accessed January 7, 2015, <http://www.iop.org/resources/energy/index.html>.
- Energy.gov, 'Fuel Cells - Basics | Department Of Energy', last modified 2015, accessed January 27, 2015, <http://energy.gov/eere/fuelcells/fuel-cells-basics>.
- Erwin, Sandra “How Much Does the Pentagon Pay for a Gallon of Gas?,” National Defense, April, 2010, <http://www.nationaldefensemagazine.org/archive/2010/April/Pages/HowMuchforaGallonofGas.aspx>
- Francis, David “Each Injured Us Soldier Will End up Costing \$2 Million on Average,” Fiscal Times, May 15, 2013, accessed December 14, 2014, <http://www.businessinsider.com/it-will-cost-2-million-for-each-injured-us-soldier-from-iraq-and-afghanistan-2013-5>.
- Fuelcelltoday.com, 'Fuel Cell Benefits - Fuel Cell Today', last modified 2015, accessed January 27, 2015, <http://www.fuelcelltoday.com/about-fuel-cells/benefits>.
- Gammons, Brad 'Technology Gains Are Powering Wind Energy (Op-Ed)', Livescience.Com, last modified 2013, accessed December 15, 2014, <http://www.livescience.com/40525-tech-gains-powering-wind-energy.html>.
- Glenn, David “The Future of Solar: Solar Power to Surge in 2014?,” CleanTechnica.com, April 05, 2014, accessed January 25, 2015, <http://cleantechnica.com/2014/04/05/future-solar-solar-power-surge-2014/>.
- Grätzel Michael Philosophical Transactions: Mathematical, Physical and Engineering Sciences, Vol. 365, No. 1853, Energy for the Future (Apr. 15, 2007), pp. 993-1005 <http://www.jstor.org/stable/25190484>
- House Committee on Subcommittee on Readiness, Committee on Armed Services, Increased Attention on Fuel Demand Management at DOD’s Forward-Deployed Locations Could Reduce Operational Risks and Costs, 111th Cong., 1st sess., 2009, H. Rep. GAO-09-388T, 1-10.
- [Http: //www.nrel.gov/ncpv/images/efficiency\\_chart.jpg](http://www.nrel.gov/ncpv/images/efficiency_chart.jpg),” National Center for Photovoltaics, accessed December 23, 2014, <http://www.nrel.gov/ncpv/>
- Insolation." Merriam-Webster.com. Merriam-Webster, n.d. Web. 25 Jan. 2015. <<http://www.merriam-webster.com/dictionary/insolation>>.

Johnson, Keith 'Fighting Form: Military Takes On Battery Fatigue', WSJ, last modified 2012, accessed February 1, 2015,  
<http://www.wsj.com/articles/SB10001424052702304371504577405982280891076>.

Knier, Gil. "How Do Photovoltaics Work?" - NASA Science. January 1, 2002. Accessed December 7, 2014. <http://science.nasa.gov/science-news/science-at-nasa/2002/solarcells/>.

Lazard Corporation,. *Lazard's Levelized Cost Of Energy Analysis – Version 8.0*. Lazard, 2014. Accessed February 22, 2015.  
<http://www.lazard.com/PDF/Levelized%20Cost%20of%20Energy%20-%20Version%208.0.pdf>.

Maryland Technology Enterprise Institute, Meet The Potential Future Of Electricity Generation Redox Power Systems, UMD Develop Breakthrough Fuel Cells That Bring Efficient, Green, Affordable, Always-On Electricity To Businesses And Homes, 2014, accessed February 1, 2015,  
[http://mtech.umd.edu/news/press\\_releases/redox\\_wachsman\\_fuel\\_cells.html](http://mtech.umd.edu/news/press_releases/redox_wachsman_fuel_cells.html).

Morrison, Charles 'Technological Superiority No Longer Sufficient For US Military Dominance - AEI', AEI, last modified 2014, accessed February 5, 2015,  
<https://www.aei.org/publication/technological-superiority-no-longer-sufficient-for-us-military-dominance/>.

Nersesian, Roy L. *Energy for the 21st Century: A Comprehensive Guide to Conventional and Alternative Sources* (Armonk, N.Y.: M.E. Sharpe, ©2007), 312, accessed January 6, 2015

Nrl.navy.mil, 'Photovoltaic Cells Tap Underwater Solar Energy - U.S. Naval Research Laboratory', last modified 2012, accessed February 6, 2015,  
<http://www.nrl.navy.mil/media/news-releases/2012/photovoltaic-cells-tap-underwater-solar-energy>

Office of Naval Research, <http://www.onr.navy.mil/en/Media-Center/Press-Releases/2013/MAPS-Marine-Solar-Power-System.aspx>.

Onr.navy.mil, 'Ion Tiger - Office Of Naval Research', last modified 2015, accessed February 1, 2015, <http://www.onr.navy.mil/Media-Center/Fact-Sheets/Ion-Tiger.aspx>.

ONR.navy.mil, 'Media Release: Solar Energy Powers Marines On Battlefield - Office Of Naval Research', last modified 2009, accessed February 6, 2015,  
[http://www.onr.navy.mil/en/~link.aspx?\\_id=685466B603734B9DB20FCFA8F3883E23&\\_z=z](http://www.onr.navy.mil/en/~link.aspx?_id=685466B603734B9DB20FCFA8F3883E23&_z=z).



- Overton, Thomas 'Fuel Cell Unit Could Replace Tactical Diesel Generators For U.S. Military', Power, 2013, accessed January 27, 2015, <http://www.powermag.com/fuel-cell-unit-could-replace-tactical-diesel-generators-for-u-s-military/?printmode=0>.
- Pierson, Logan DoD Power, Energy & Propulsion, 2015, accessed February 5, 2015, [http://www.tacticaldefensemedia.com/pdf/dod/2012\\_Q2.pdf](http://www.tacticaldefensemedia.com/pdf/dod/2012_Q2.pdf).
- Ridden, Paul “V3solar Puts a New Spin On Pv Efficiency,” Gizmag, September 30, 2012, 1, accessed January 25, 2015, <http://www.gizmag.com/v3solar-spin-cell/24352/>.
- Roller, Emma 'Hike, Kick, And Dance To Charge Your Gadgets', Slate Magazine, last modified 2015, accessed January 27, 2015,
- Rose, Robert Fuel Cells: Civilian And Military, PDF, 1st ed., 2008, accessed January 31, 2015, <http://www.fuelcells.org/uploads/rosemilitary.pdf>.
- Sheppard, Dennis G. United States. NASA Contractor Report 4337, DOE/NASA/5226-1 Historical Development of The Windmill. Washington, D.C.: National Aeronautics and Space Administration, 1990.
- Sofge, Erik “The Energy Fix: Reinventing the Solar Array: Reinventing the array could usher in a new age for solar,” Popular Science, June 11, 2013, 1, accessed January 25, 2015, <http://www.popsoci.com/science/article/2013-05/future-energy-solar>.
- Solar Power (Technology and Economics),” Electropedia, accessed January 25, 2015, [http://www.mpoweruk.com/solar\\_power.htm](http://www.mpoweruk.com/solar_power.htm).
- Towler, Brian F. The Future of Energy (London: Academic Press, 2014), 161-68, accessed December 7, 2014, <http://proquest.tech.safaribooksonline.de/9780128010273>.
- Trimarchi, Maria “Harvesting Energy from Human Movement,” How Stuff Works, accessed January 7, 2015, <http://science.howstuffworks.com/environmental/green-science/house-music-energy-crisis1.htm>.
- U.S. Army Field Manual 3-34.400 (FM 5-104) General Engineering, December 2008; p. E-6
- U.S. Department of Defense, Fiscal Year 2012. Operational Energy Annual Report, open-file report, U.S. DoD (Washington, DC: Government Printing Office, 2013), [http://energy.defense.gov/Portals/25/Documents/Reports/20131015\\_FY12\\_OE\\_Annual\\_Report.pdf](http://energy.defense.gov/Portals/25/Documents/Reports/20131015_FY12_OE_Annual_Report.pdf)

U.S. Department of Defense, Fiscal Year 2012. Operational Energy Annual Report, open-file report, U.S. DoD (Washington, DC: Government Printing Office, 2013).

U.S. House Committee on Subcommittee on Readiness, Committee on Armed Services, Increased Attention on Fuel Demand Management at DOD's Forward-Deployed Locations Could Reduce Operational Risks and Costs, 111th Cong., 1st sess., 2009, H. Rep. GAO-09-388T, 1-10

Wang, Ucilia "Perovskite Offers Shot at Cheaper Solar Energy," Wall Street Journal, Sept. 28, 2014, accessed January 25, 2015, <http://www.wsj.com/articles/perovskite-offers-shot-at-cheaper-solar-energy-1411937799>.

What Is Operational Energy?" Assistant Secretary of Defense for Operational Energy Plans and Programs, accessed November 17, 2014, <http://energy.defense.gov/About.aspx>.

Wpafb.af.mil, 'Air Force Small Wind Research Improves Resiliency, Reduces Fossil Fuels Demand', last modified 2013, accessed February 6, 2015, <http://www.wpafb.af.mil/news/story.asp?id=123363697>.

## LCDR JOSEPH H. PETH

Lieutenant Commander Peth is a native of Savannah, Georgia and is an alumnus of Georgia Southern University. He has a Master of Business Administration degree from the Naval Post Graduate School with a concentration in Supply Chain Management.

He enlisted in the United States Navy in 1987 and served in USS Excel (MSO-439), COOPMINEUNIT 2209 at Savannah, GA and IBU27 at Charleston, SC. He was selected for the Officer Candidate Program in Pensacola, Florida and received his commission as a Navy Supply Corps Officer in June 2000.

His afloat tours were Disbursing Officer in USS Taylor (FFG 50) and Supply Officer in USS Lake Erie (CG 70). His ashore tours include Foreign Military Sales instructor at Navy Supply Corps School, Athens, GA; N4 at Naval Special Warfare Unit Three in Manama, Bahrain; and the Expeditionary Logistics Officer at Commander, Naval Special Warfare Command in Coronado, CA. He is a member of the Acquisition Professional Community and has earned supply warfare qualifications in expeditionary logistics and surface warfare.